Multi-scenario Simulation of Ecosystem Services and Their Trade-offs and Synergies: A Case Study of the Shanxi Section of the Yellow River Basin (Postprint)

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Abstract

The Shanxi section of the Yellow River Basin represents a critical ecological barrier zone in China, where forecasting future trade-offs and synergies among ecosystem services is essential for optimized ecosystem management.

Accordingly, this study employed system dynamics, a patch-level land use change simulation model (PLUS), and root mean square deviation to analyze the supply and demand of ecosystem services (water yield, soil conservation, and carbon sequestration services) and their trade-off/synergy relationships under five 2030 scenarios: natural development, economic development, ecological protection, integrated development, and carbon peak.

The results indicate that: (1) Under the economic development scenario, water yield service supply reaches its maximum at 73.27 mm, while the ecological protection scenario exhibits the lowest demand for water yield and carbon sequestration services at 59.89 mm and 14.92 t C · hm-2, respectively. (2) The ecological protection scenario demonstrates the lowest trade-off degree between water yield and soil conservation services, as well as between water yield and carbon sequestration service supply, while concurrently showing lower synergy intensity among the demands for water yield and soil conservation, and water yield and carbon sequestration services. (3) Both ecological protection and carbon peak scenarios exhibit supply-demand ratios greater than 0 for water yield and carbon sequestration services, with similar supply-demand ratios for soil conservation services across all scenarios.

Therefore, future development in the Shanxi section of the Yellow River Basin should optimize land use patterns, balance ecological security with socio-economic development, achieve the carbon peak target, and establish a foundation for realizing the carbon neutrality goal.

Full Text

Multi-scenario Simulation of Ecosystem Services and Their Trade-off/Synergy Relationships: A Case Study of the Shanxi Section of the Yellow River Basin

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Abstract: The Shanxi section of the Yellow River Basin serves as a vital ecological barrier in China, making the prediction of future ecosystem service trade-offs and synergies crucial for optimized ecosystem management. This study employs system dynamics, a patch-level land use change simulation model (PLUS), and root mean square deviation analysis to examine the supply and demand of ecosystem services—including water yield, soil conservation, and carbon sequestration—and their trade-off/synergy relationships under five scenarios for 2030: natural development, economic development, ecological protection, comprehensive development, and carbon peak. The results reveal: (1) The economic development scenario yields the highest water supply at 73.27 mm, while the ecological protection scenario shows the lowest demand for water yield and carbon sequestration services at 59.89 mm and 14.92 t $C \cdot hm^{-2}$, respectively. (2) The ecological protection scenario exhibits the lowest trade-off intensity between water yield and soil conservation as well as between water yield and carbon sequestration, with both supply and demand showing low synergy intensity. (3) The supply-demand ratios for water yield and carbon sequestration exceed 1 under ecological protection and carbon peak scenarios, while soil conservation service ratios remain consistent across all scenarios. Therefore, future development in the Shanxi section should optimize land use patterns, balance ecological security with economic and social development, achieve the "carbon peak" target, and establish a foundation for "carbon neutrality."

Keywords: ecosystem services; trade-offs/synergies; scenario simulation; PLUS model; Shanxi section of the Yellow River Basin

1.1 Study Area Overview

The Shanxi section of the Yellow River Basin (110°12 –113°38 E, 34°33 – 40°19 N) enters Shanxi at Pianguan County and exits at Nianpan Valley in Yuanqu County, passing through Shuozhou, Xinzhou, Lüliang, Taiyuan, and other cities. The region primarily comprises loess hilly-gully areas, rocky mountainous areas, and valley plain zones [Figure 1: see original paper]. The loess hilly-gully area is dominated by mound-shaped and ridge-shaped hills with fragmented terrain and crisscrossing gullies. The rocky mountainous area features better vegetation conditions and serves as an important water conservation zone on the Loess Plateau. The valley plain area has flat terrain and relatively light soil erosion. The study area has a temperate continental monsoon climate with cold, dry winters and warm, rainy summers, with annual precipitation of 400–650 mm. Vegetation types transition from south to north as deciduous broadleaf forests, coniferous forests, and shrublands. However, due to long-term human activities and rapid economic development, the region faces multiple pressures including vegetation restoration, soil conservation, and energy pollution, necessitating research on ecosystem service trade-off/synergy relationships.

1.2 Data Sources

This study incorporates meteorological data, soil data, land use data, digital elevation models, normalized difference vegetation index, socioeconomic data, and road network data. Detailed information on data years, resolution, and sources is provided in .

1.3.1 Land Use Change Simulation Based on the PLUS Model

The PLUS model is a raster-based cellular automata model designed to predict dynamic changes in land use patches. This study selected 13 driving factors including slope aspect, elevation, nighttime light, population density, precipitation, slope gradient, soil texture, and distances to primary, secondary, and tertiary roads, cities, and rivers to simulate five scenarios for the Shanxi section of the Yellow River Basin.

Natural Development Scenario: Land use transitions follow historical patterns based on a Markov chain transition matrix. **Economic Development Scenario:** Transition probabilities for converting cultivated land, forest, grassland, and water areas to construction land increase by 20%, while conversion from construction land back to forest/grassland decreases by 20%. **Ecological Protection Scenario:** Transition probabilities for converting cultivated land and forest to construction land decrease by 30%, while conversion from construction land back to forest/grassland increases by 30%. **Comprehensive Development Scenario:** Transition probabilities for converting cultivated land, forest, grassland, and water areas to construction land decrease by 10%, while conversion from construction land back to forest/grassland increases by 10%. **Carbon Peak Scenario:** Transition probabilities for converting cultivated land, forest, grassland, and water areas to construction land decrease by 20%, while conversion from construction land back to forest/grassland increases by 20%.

1.3.2 Assessment of Ecosystem Service Supply

Water Yield Service: The InVEST model's water yield module assesses water supply based on the water balance principle, calculating the difference between precipitation and actual evapotranspiration:

$$WY_i = P_i - AET_i$$

where WY_i is the annual water yield supply (mm), P_i is annual precipitation (mm), and AET_i is annual actual evapotranspiration (mm).

Soil Conservation Service: The InVEST sediment delivery ratio module evaluates soil conservation supply:

$$SC_i = RK_i \times LS_i \times (1 - C_i \times P_i) \times SDR_i$$

where SC_i is soil conservation amount ($\mathrm{t \cdot hm^{-2}}$), RK_i is rainfall erosivity factor, LS_i is topographic factor, C_i is vegetation cover management factor, P_i is soil conservation practice factor, and SDR_i is sediment delivery ratio.

Carbon Sequestration Service: Carbon sequestration supply is calculated through carbon fixation rates:

$$CS = \sum_{x=1}^{6} (FVCSR_x + FSCSR_x) \times SF_x \times A$$

where CS is annual ecosystem carbon sequestration ($\mathrm{t\ C \cdot hm^{-2}}$), x represents forest, grassland, freshwater, farmland, and urban ecosystems, $FVCSR_x$ is vegetation carbon sequestration rate, $FSCSR_x$ is soil carbon sequestration rate, SF_x is ecosystem area, and A is watershed area.

1.3.3 Assessment of Ecosystem Service Demand

Water Yield Service: A system dynamics model was constructed to predict water demand (FIGURE:2), incorporating industrial, agricultural, domestic, and ecological water consumption. Five scenarios were designed:

- **Natural Development:** Industrial output growth rate of 7.5%, with irrigation quotas and livestock water demand predicted by system dynamics.
- **Economic Development:** Industrial output growth rate of 9.5%, other parameters same as natural development.
- **Ecological Protection:** Industrial output growth rate of 6.5%, urban and rural domestic water quotas reduced by 13.5%, industrial water use per output, irrigation quotas, and livestock water demand reduced by 20%.
- **Comprehensive Development:** Industrial output growth rate of 8.5%, all water quotas reduced by 10%.
- **Carbon Peak Scenario:** Industrial output growth rate of 7.5%, domestic water quotas reduced by 13.5%, other quotas reduced by 15%.

Soil Conservation Service: Demand is assessed as potential soil erosion:

$$E_i = USLE_i \times SDR_i$$

where E_i is soil erosion amount ($\mathrm{t \cdot hm^{-2}}$) and $USLE_i$ is actual soil erosion.

Carbon Sequestration Service: A carbon emission model was constructed based on system dynamics (FIGURE:3), incorporating social, economic, energy, and emission indicators. Five scenarios were established with varying industrial growth rates and energy consumption patterns.

1.3.4 Ecosystem Service Trade-off and Synergy Intensity

Trade-off Intensity: Root mean square deviation (RMSD) measures trade-off intensity among ecosystem services:

$$RMSD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ES_{std_i} - \overline{ES_{std}})^2}$$

where ES_{std_i} is standardized ecosystem service value, ES_{std} represents standardized data, ES_i is actual value, ES_{max} and ES_{min} are maximum and minimum values, and n is the number of services.

Synergy Intensity: Synergy is defined as the inverse of trade-off intensity, representing the vertical distance from the 1:1 line:

$$Synergy = 1 - RMSD$$

Supply-Demand Matching: The ecosystem service supply-demand ratio (ESDR) evaluates matching status:

$$ESDR = \frac{S - D}{(S_{max} + D_{max}) \div 2}$$

where S is supply, D is demand, and $ESDR > 0$ indicates supply exceeds demand, $ESDR = 0$ indicates balance, and $ESDR < 0$ indicates supply shortage.

2.1 Spatial Patterns of Ecosystem Service Supply and Demand Under Different Scenarios

2.1.1 Water Yield Service Supply and Demand Spatial Patterns

Under natural development, economic development, ecological protection, comprehensive development, and carbon peak scenarios, water yield supplies are 72.99 mm, 73.27 mm, 71.60 mm, 72.77 mm, and 71.65 mm, respectively, with economic development showing the highest supply [Figure 4: see original paper]. Water yield demands are 82.82 mm, 70.33 mm, 59.89 mm, 63.92 mm, and

79.22 mm, respectively, with ecological protection showing the lowest demand due to reduced water quotas [Figure 5: see original paper]. Spatially, both supply and demand exhibit a "low in northwest, high in southeast" pattern, with low-value areas concentrated in loess hilly-gully regions and high-value areas in rocky mountainous and valley plain zones [FIGURE:6, FIGURE:7].

2.1.2 Soil Conservation Service Supply and Demand Spatial Patterns

Soil conservation supply and demand amounts are similar across all five scenarios. Spatially, both soil conservation and erosion show a "low in northeast, high in southwest" pattern, with high values concentrated in loess hilly-gully areas and low values in rocky mountainous regions. The loess hilly-gully area exhibits high actual erosion rates (demand) and steep slopes (potential erosion), resulting in high soil conservation supply. These findings underscore the need to consolidate achievements from the Grain-for-Green Program and enhance soil conservation capacity.

2.1.3 Carbon Sequestration Service Supply and Demand Spatial Patterns

Carbon sequestration supplies are similar across scenarios [Figure 4: see original paper], with demands of 25.39 t $C \cdot hm^{-2}$, 30.42 t $C \cdot hm^{-2}$, 14.92 t $C \cdot hm^{-2}$, 23.86 t $C \cdot hm^{-2}$, and 23.28 t $C \cdot hm^{-2}$, respectively. Ecological protection shows the lowest demand due to reduced industrial growth and energy consumption. Spatially, carbon sequestration supply is higher in rocky mountainous and loess hilly-gully areas, while demand shows a "low in northwest, high in southeast" pattern, with high values in valley plains where population and economic activity concentrate.

2.2 Spatial Variation Characteristics of Trade-off and Synergy Intensities

2.2.1 Supply-Supply Trade-off Intensity

Water yield shows trade-off relationships with soil conservation and carbon sequestration [1]. Trade-off intensities between water yield and soil conservation, and between water yield and carbon sequestration are similar across scenarios [Figure 8: see original paper]. Natural development and economic development scenarios show relatively high trade-off intensities, while ecological protection shows the lowest. Water yield depends on precipitation and evapotranspiration, while soil conservation relates to vegetation and slope, and vegetation cover directly affects carbon sequestration. Economic development features lower forest coverage, reduced evapotranspiration, highest water yield supply, but also highest soil erosion and lowest carbon sequestration capacity, resulting in the strongest trade-offs. High trade-off intensity zones are located in valley plains and rocky mountainous areas, while low intensity zones are in loess hilly-gully regions [Figure 9: see original paper].

2.2.2 Demand-Demand Synergy Intensity

Water yield demand shows synergy with soil conservation and carbon sequestration demands [2]. Synergy intensities are similar across scenarios, with ecological protection and carbon peak scenarios showing relatively low synergy, while economic development shows higher synergy. The economic development scenario features the highest industrial growth, water quotas, and energy consumption, leading to highest water demand and carbon emissions, but relatively low forest coverage and high soil erosion. Consequently, water demand synergizes strongly with both soil conservation and carbon sequestration demands. Spatially, water-soil conservation demand synergy is highest in loess hilly-gully areas, while water-carbon synergy is highest in valley plains [Figure 9: see original paper].

2.2.3 Supply-Demand Trade-off Intensity

Supply-demand ratios for water yield are 0.88, 1.04, 1.20, 1.14, and 0.90 across scenarios, with ecological protection showing the highest ratio, followed by carbon peak scenario [Figure 10: see original paper]. Water supplies are similar across scenarios, but ecological protection has the lowest demand due to reduced quotas, resulting in the highest supply-demand ratio. Soil conservation supply-demand ratios are similar across all scenarios and consistently below 1. Carbon sequestration supply-demand ratios are relatively high under ecological protection and carbon peak scenarios but lowest under economic development. Spatially, water yield supply-demand ratios are high in loess hilly-gully areas but low in valley plains where dense populations and rapid development create demand-supply imbalances [Figure 11: see original paper].

3 Discussion

3.1 Influencing Factors of Ecosystem Service Trade-off/Synergy Relationships

Water yield supply is primarily influenced by precipitation and evapotranspiration, while soil conservation depends on vegetation, slope, and soil properties. Carbon sequestration relates to land use type and vegetation coverage. High forest coverage enhances evapotranspiration, reducing water yield supply, while steep slopes and high vegetation cover increase soil conservation, creating trade-offs between water yield and soil conservation [3]. High forest coverage also increases carbon sequestration while reducing water yield through strong evapotranspiration, resulting in water-carbon trade-offs [4]. Flat terrain with low vegetation cover experiences high soil erosion and rapid urbanization, creating high water demand that synergizes with soil conservation demand. Areas with high population density and rapid industrial development exhibit large water demand and carbon emissions, generating synergy between water and carbon demands [5].

3.2 Impact of Land Use on Ecosystem Service Trade-offs

Ecological protection scenarios produce the lowest water yield but highest soil conservation and carbon sequestration, consistent with previous research [6]. Economic development scenarios show the highest water-carbon demand synergy due to high soil erosion, water conservation emphasis, and reduced water consumption [7]. The trade-off intensities between water-soil conservation and water-carbon are similar across scenarios because forest areas and evapotranspiration rates are comparable [8]. However, these findings differ from some regional studies where urban expansion increased impervious surfaces and water yield [9], highlighting context-specific relationships.

3.3 Limitations

The PLUS model predicted land use for 2030 based on 2020 data with robust accuracy (Kappa = 0.82). However, climate change and policy impacts were excluded, limiting representation of future possibilities [10]. Methodological optimization with advanced data processing and modeling techniques is needed to improve analytical accuracy and sensitivity.

4 Conclusions

Using the PLUS model and system dynamics, this study predicts ecosystem service supply, demand, and trade-off/synergy intensities under five scenarios for the Shanxi section of the Yellow River Basin. Key conclusions are:

1. Ecological protection scenarios show lowest water demand (59.89 mm), while economic development shows highest water supply (73.27 mm). Soil conservation and carbon sequestration exhibit distinct spatial patterns across scenarios, closely related to topography, vegetation cover, and human activity intensity.

2. Economic development scenarios show relatively high trade-off intensities between water yield and soil conservation/carbon sequestration due to reduced forest coverage and increased construction land. Ecological protection scenarios minimize trade-offs, while economic development scenarios show high demand synergy due to increased water quotas and energy consumption.

3. Supply-demand ratios for water yield and carbon sequestration exceed 1 under ecological protection and carbon peak scenarios. Trade-off intensities are high in valley plains, while water-soil conservation demand synergy is high in loess hilly-gully areas, and water-carbon demand synergy peaks in valley plains. These results emphasize the need to enhance soil conservation and carbon sequestration capacity to address climate change and achieve carbon reduction targets.

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Note: Figure translations are in progress. See original paper for figures.